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A Simple Method for Processing Measurements of Vehicle Response to Underbody Blast during Live Fire Test and Evaluation

by Robert J Spink

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Warrior Injury Assessment Manikin Project Management Office, ARL

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14. ABSTRACT As part of the Live Fire Test and Evaluation process, military vehicles for ground combat are tested against under-body threats like those recently used against Soldiers in Iraq and Afghanistan. In many cases, accelerometers are used to measure the structural response of these vehicles. The resulting data can then be used to characterize the environment of a mounted occupant in these blast events. However, it must first be processed in a robust and repeatable way to yield metrics that are relatively insensitive to nuances of data collection such as sample rate and anti-alias filtering. This report details one such method with 4 steps that produce values for peak velocity of a constitutive accelerometer record and the time taken to achieve this peak velocity. A MATLAB implementation of the method is also provided in the Appendix to the report.				
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1. Background

When testing the performance of vehicles against under-body threats such as those used in Iraq and Afghanistan, the response of a vehicle's structure is measured, in part, with accelerometers. Specifically, measurements are taken from the seats and floor as these locations are in direct contact with the occupant and thus give some insight into the loading condition experienced. This structural-response data can be combined with measurements taken from anthropomorphic test devices placed at crew positions to provide valuable information regarding the interaction between vehicle's components and occupants. These data can be used to characterize the environment that the mounted occupant is exposed to and inform changes to the design of vehicular components to enhance crew survivability.

Drawing insights from accelerometer data is not necessarily intuitive as the quantitative and qualitative characteristics of the data are largely influenced by their measured frequency content. This content, not readily discernible through visual inspection, is influenced by sample rate and the need to prevent aliasing by implementing hardware filters.

This point is illustrated with a simplified example of a test article exposed to a blast event. The response of the fictitious test article, shown in Fig. 1, is composed of superimposed accelerations with magnitudes of $1,000 \text{ m/s}^2$ and $10,000 \text{ m/s}^2$ and frequencies of 50 Hz and 10 kHz, respectively.

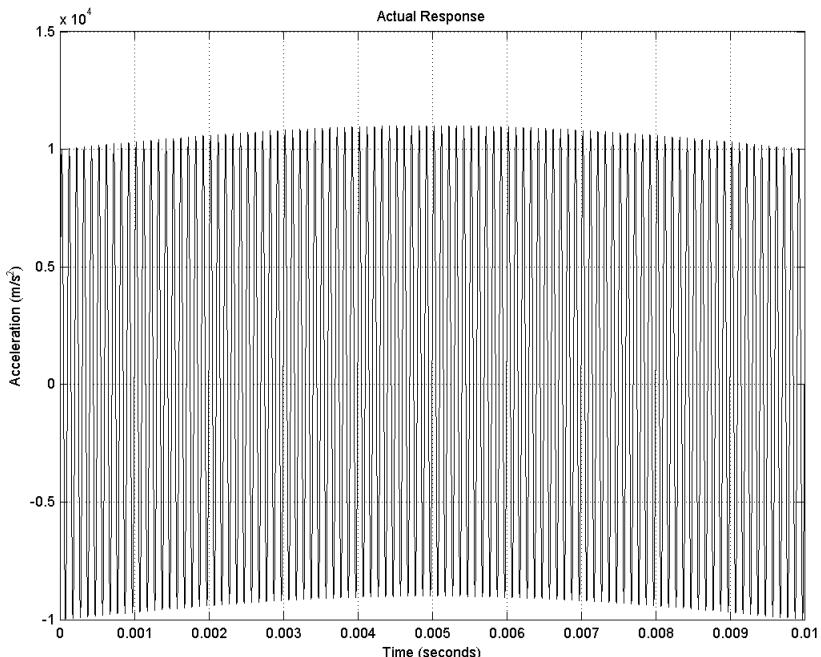


Fig. 1 The contrived response of a test article exposed to a blast event

Environments with accelerations between 300 g to 1,000,000 g and including mixed frequency content between 10 Hz and 1 MHz are classified as “ballistic shock” by MIL-STD-810G, a military standard used during Live Fire Test and Evaluation (LFT&E) tests for underbody blast.¹ Though fictional, this example meets these criteria and can therefore be considered a ballistic-shock event. The measurement techniques used to characterize it should therefore include instrumentation with a “flat frequency response to at least 100 kHz”, a digitizing rate “at least 2.5 times” the anti-alias (AA) filter frequency, and AA filtering that provides “an attenuation of 50 dB or greater for frequencies that will fold back into the passband”.¹ The “measured” accelerations are compared in Fig. 2, where they are sampled at 100 kHz and 20 kHz with AA filters of 40 kHz and 8 kHz, respectively, each simulated as digital 4-pole Butterworth filters.

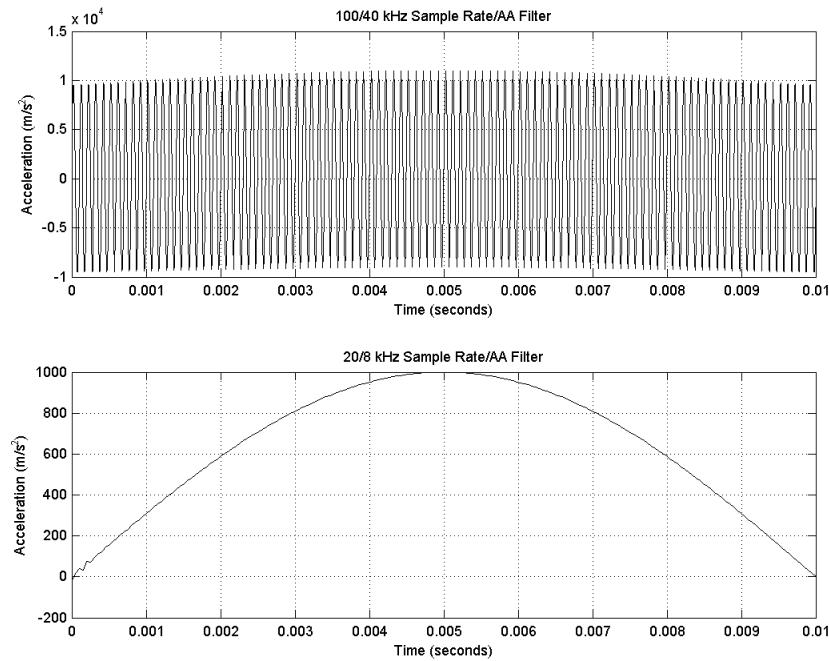


Fig. 2 Acceleration measured with 100 kHz and 20 kHz sample rates

Not surprisingly, the 8 kHz AA filter required by MIL-STD-810G with the 20 kHz sample rate removed the contribution of the 10 kHz acceleration while the 40 kHz AA filter required with the 100 kHz sample rate did not. Perhaps more importantly from an assessment standpoint, the restriction of data bandwidth to 8 kHz reduced the peak acceleration by more than 90% as compared to applying the 40 kHz filter. Since it is possible for the bandwidth of LFT&E data to vary, this example underscores the potentially misleading nature of acceleration magnitude as a metric when analyzing structural data and the value of seeking alternatives.

For many researchers and analysts, velocity is an intuitive engineering parameter. As the integral of acceleration, it is also less susceptible to the presence or absence of relatively high-frequency content and, therefore, is an attractive alternative to acceleration-based metrics. This is easily illustrated by turning back to the simple example. Velocities for the “actual” and “measured”

responses are given in Fig. 3. The expanded view from 9.5 to 10 milliseconds shows that the reduction in maximum velocity associated with the lowest sample rate is approximately 5%.

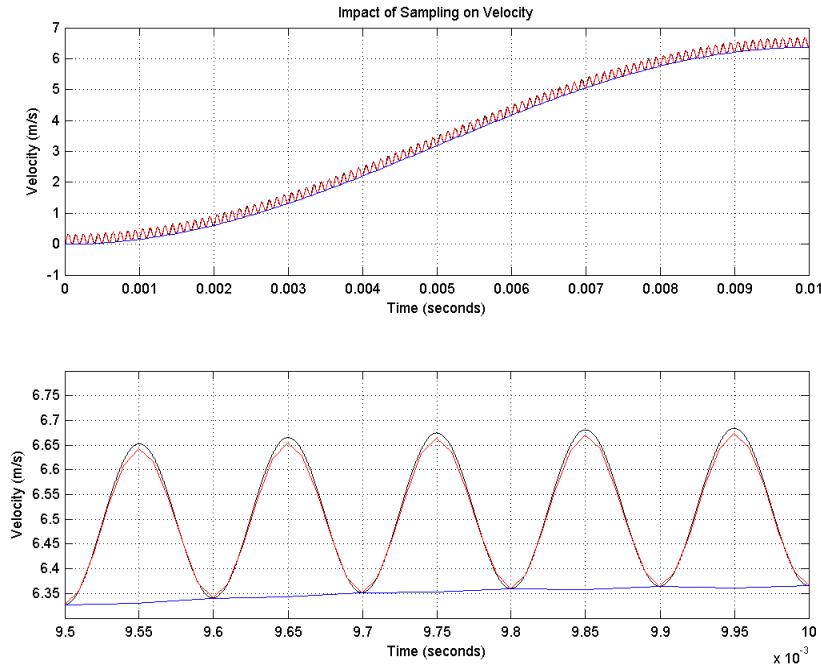


Fig. 3 Velocity from the actual acceleration data (black), 100 kHz sampled data (red), and 20 kHz sampled data (blue)

Not only is the assessed structural velocity less sensitive to the nature of the data and how they were captured, the use of peak velocity as a metric for vehicle response is useful from an occupant-injury perspective due to the known velocity-dependent nature of human tissue.^{2,3} However, since tissue has the characteristic of dissipating energy over time, it is also useful to know how quickly the assessed peak velocity is achieved. The ratio of the peak velocity to the time-to-peak velocity provides a constant pseudo-acceleration, albeit one much less susceptible to the effects of sampling and filtering.

To benefit from any metric, it is imperative that it be assessed in a uniform manner whether analyzing large amounts of data or making comparisons between test events. So it is, too, for the calculation of peak velocity and time-to-peak velocity. To achieve the goal of calculating these parameters uniformly, a codified and automated process should exist that is applicable to as many valid structural responses as possible. One such process is described in the next section with an example and provided in the form of a MATLAB script in the Appendix.

2. Methodology

2.1 Calculation Method

The following steps detail a simple method for calculating peak velocity and time-to-peak velocity from an acceleration record. The first step is to apply baseline shifts to the acceleration data. Following integration, the appropriate peak velocity is identified. The slope of the velocity rise is then calculated and used to determine time-to-peak velocity. Issues such as rotation of the test article, time misalignment, aliasing, clipping, and other data-acquisition issues are not addressed here but should be avoided and, if possible, reconciled prior to the implementation of this method.

2.1.1 Step 1 – Baseline Shifts

Two distinct baseline adjustments are made to the acceleration record prior to integration. In the first, the mean pre-trigger acceleration is subtracted from the entire data record to remove any systemic baseline shift. If the test article comes to rest prior to the end of the data record, a second baseline adjustment is applied in which the average post-trigger acceleration is subtracted from the post-trigger data record in order to remove any residual velocity.⁴ If a non-zero velocity is present in the test article at the end of the data record, the second baseline adjustment should not be applied. As Fig. 4 shows, these shifts do not noticeably alter the acceleration record but provide a meaningful correction to the velocity trace. This correction is small at early times in the velocity record but more substantial at later times due to the accumulation of error when integrating the acceleration data.

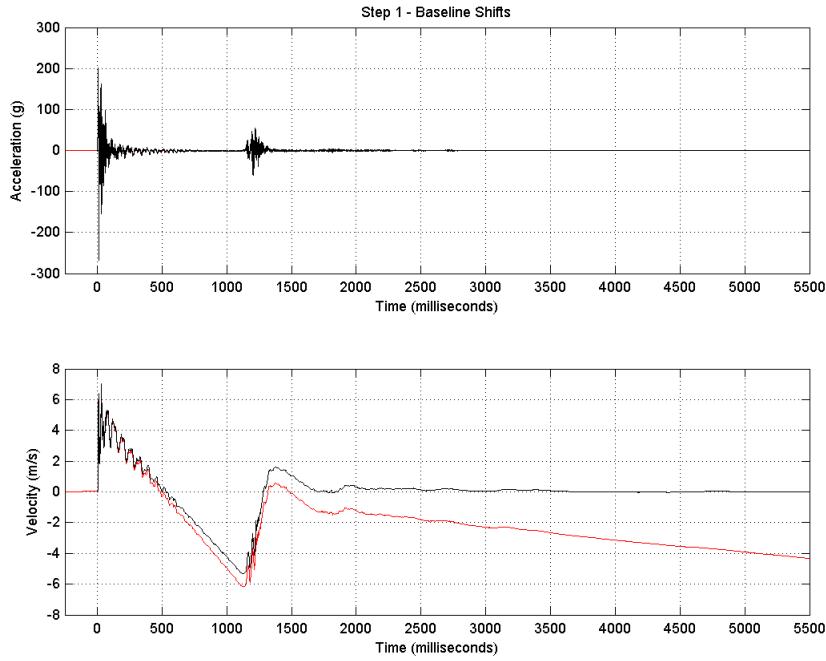


Fig. 4 Acceleration and velocity from the original (red) and baseline shifted (black) data

2.1.2 Step 2 – Locate the Peak

Following integration of the acceleration record, the peak velocity within a time frame of interest is identified. However, this point does not always represent the end to the initial rise in velocity; for example, it could be a secondary peak that occurs much later in time than the initial velocity rise, as shown in Fig. 5. Choosing the secondary peak as the peak velocity would enlarge the time-to-peak velocity and therefore suggest a milder loading on the occupant than what actually occurred. This is resolved by first finding all local maxima in the velocity record that have a magnitude greater than 90% of the absolute peak. The local maximum just prior to the absolute peak is then selected as the new peak velocity. This search is repeated with the new peak velocity from the previous iteration until no local maxima exist that meet the 90% threshold. It should be noted that 90% was generally found to be the largest threshold that yielded the same local maximum as analysts chose for a majority of the LFT&E cases examined during the construction of this method.

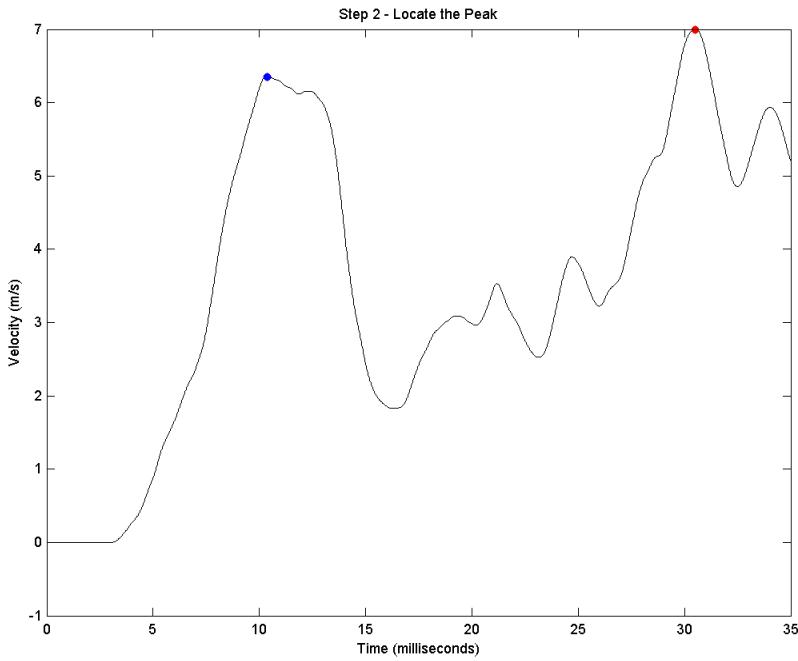


Fig. 5 The absolute (red) and final (blue) peak velocities

2.1.3 Step 3 – Calculate Velocity Slope

Once the final peak velocity has been identified, an assumption of constant acceleration is used to define a velocity slope. Three locations on the velocity trace between the start of the time frame of interest and the peak velocity must be found. They are the first data points that have velocity magnitudes exceeding 5%, 20%, and 95% of the final peak velocity. The first and last points are the start and end points, respectively, of the velocity slope. If the velocity record exhibits a monotonic rise between the 5% and 20% points (no negative derivatives are present), it is appropriate to set the start of the velocity slope relative to the difference between the final peak velocity and zero as shown in Fig. 6. If there is at least one negative derivative in the 5% to 20% time window of the velocity record, the starting point of the slope must be recalculated.

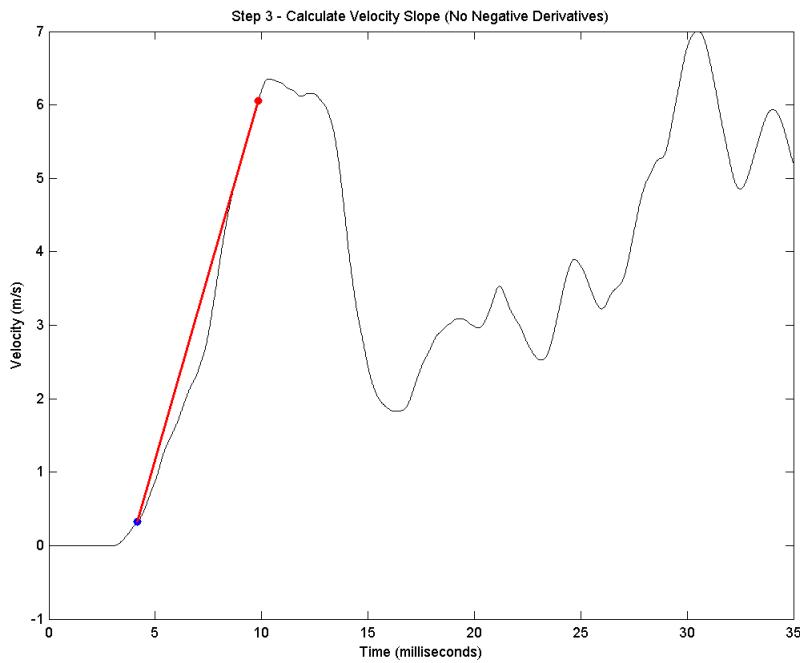


Fig. 6 Velocity slope from 5% (blue) to 95% (red) of the final peak velocity

To recalculate the starting point of the velocity slope, the data point immediately following the last negative derivative in the window is identified and used to replace zero as the baseline for the 5% calculation. In other words, the velocity slope now travels from 5% of the difference between the final peak velocity and the point after the last negative derivative to 95% of the difference between the final peak velocity and zero (as shown in Fig. 7).

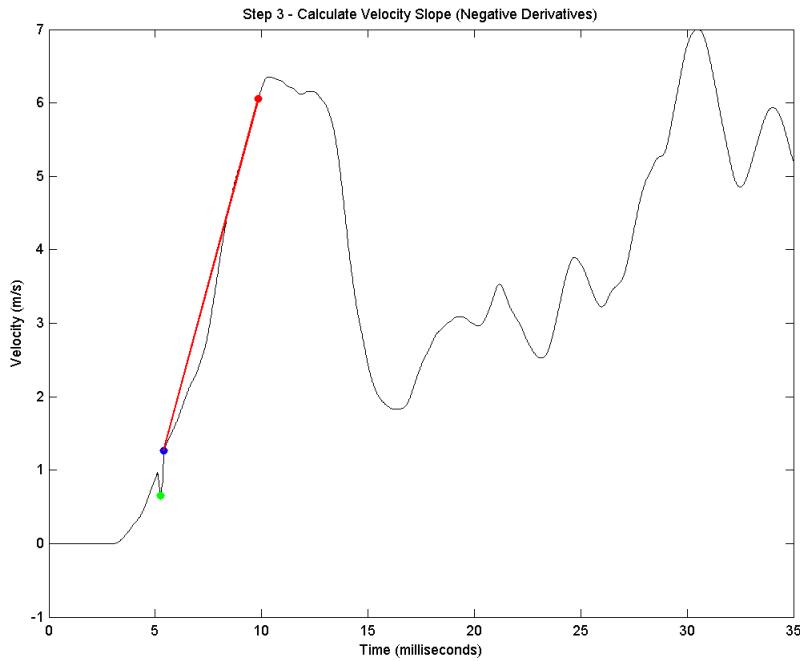


Fig. 7 Velocity slope from 5% (blue) of the difference between the final peak velocity and the point after the last negative derivative (green) to 95% (red) of the difference between the final peak velocity and zero

2.1.4 Step 4 – Calculate Time-to-Peak

Finding the start and end times of the velocity approximation is accomplished by extending the slope line (Fig. 8). The start time is the intercept between the slope line and zero velocity, and the end time is the intercept between the slope line and peak velocity. Time-to-peak is simply the difference between the end and start times.

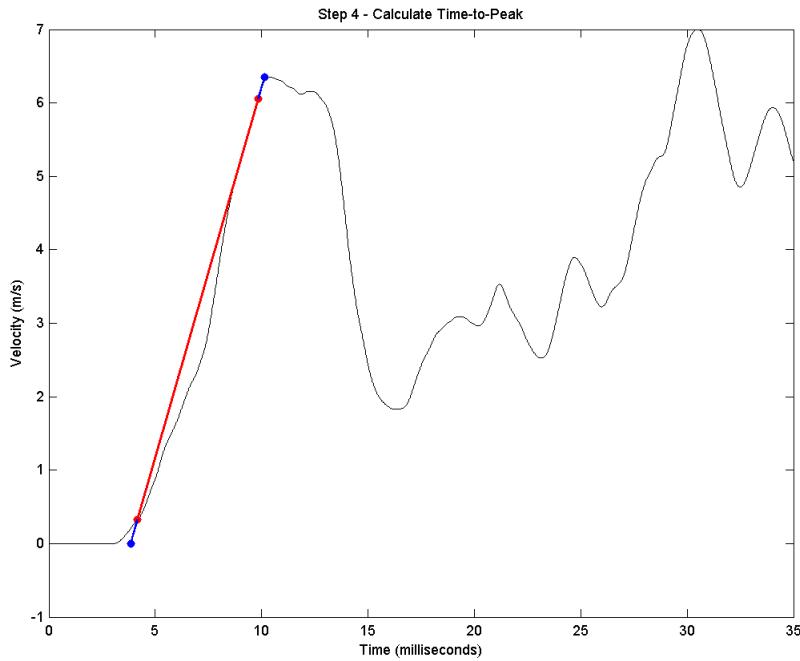


Fig. 8 The full approximation of the rise in velocity formed by extending (blue) the velocity slope (red) developed in Step 3

3. Conclusion

The simple method explained in this report was developed to be applicable to a large number of structural-velocity traces produced during LFT&E with a broad range of characteristics. It approximates the velocity of a structural component from the constituent acceleration record in order to determine peak velocity and the time taken to achieve peak velocity. Together, these metrics are useful when assessing the response of a vehicle exposed to an underbody-blast event and, consequently, characterizing the environment of mounted vehicle occupants.

4. References

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2. Yoganandan N, Pintar F, Butler J, Reinartz J, Sances A, Larson SJ. Dynamic response of human cervical spine ligaments. *Spine*. 1989;14(10):1102–1110.
3. Nordin M, Frankel VH. Basic biomechanics of the musculoskeletal system, 3rd ed. New York (NY): Lippincott Williams and Wilkins; 2001.
4. Gaberson HA. Pseudo velocity shock spectrum analysis data editing. Paper presented at: IMAC-XXVII. Proceedings of the SEM Conference & Exposition on Structural Dynamics; 2009 Feb 9–12; Orlando (FL).

Appendix. MATLAB Script for Calculating Peak and Time-to-Peak Velocities

This appendix appears in its original form, without editorial change.

```

%Velocity and Time-to-peak Script
%Robert Spink, 26 June 2014

%Input variables are as follows:
%time - vector of time values
%vel - vector of velocity values
%search_start - start time for the data region of interest
%search_stop - stop time for the data region of interest

%FIND START INDEX, STOP INDEX, START THRESHOLD, MIDDLE THRESHOLD, AND STOP THRESHOLD
start_index=find(time>search_start,1);
stop_index=find(time>search_stop,1)-1;
start_threshold=.05;
mid_threshold=.2;
stop_threshold=.95;
peak_compare=.90;

%FIND ALL LOCAL PEAKS
derivative=diff(vel(start_index:stop_index));
peak_vector=zeros(stop_index-start_index,1);
for k=2:length(peak_vector);
    if ((derivative(k-1)<0&derivative(k)>0) & vel(k)<0) | ((derivative(k-1)...
        >0&derivative(k)<=0) & vel(k)>0);
        peak_vector(k)=vel(k+start_index-1);
    end
end

%PROCESS DATA
[vel_100,vel_100_index]=max(vel(start_index:stop_index));
vel_100_index=vel_100_index+start_index-1;
recursive_peak=length(find(peak_vector(1:vel_100_index-start_index+1-1)>peak_compare*vel_100));
while recursive_peak>0;
    vel_100_index=find(peak_vector(1:vel_100_index-start_index+1-1)...
        >peak_compare*vel_100,1,'last')+start_index-1;
    vel_100=vel(vel_100_index);
    recursive_peak=length(find(peak_vector(1:vel_100_index-start_index+1-1)...
        >peak_compare*vel_100));
end
time_100=time(vel_100_index);

vel_95_index=find(vel(start_index:vel_100_index-1)<vel_100*stop_threshold,1,'last')+start_index;
vel_95=vel(vel_95_index);
time_95=time(vel_95_index);

vel_20_index=find(vel(start_index:vel_95_index-1)<vel_100*mid_threshold,1,'last')+start_index;
vel_20=vel(vel_20_index);
time_20=time(vel_20_index);

vel_5_index=find(vel(start_index:vel_20_index-1)<vel_100*start_threshold,1,'last')+start_index;
vel_5=vel(vel_5_index);
time_5=time(vel_5_index);

if size(find(derivative(vel_5_index-start_index+1:vel_20_index-start_index+1)<0))>0;
    last_inflection_index=find(derivative(vel_5_index-start_index+1:vel_20_index...
        -start_index+1)<0,1,'last')+vel_5_index;
    last_inflection_vel=vel(last_inflection_index);
    vel_5_index=find(vel(start_index:vel_100_index)<(last_inflection_vel+(start_threshold*...
        (vel_100-last_inflection_vel))),1,'last')+start_index;
    vel_5=vel(vel_5_index);
    time_5=time(vel_5_index);
end

slope=(vel_95-vel_5)/(time_95-time_5);
peak_time=((vel_100-vel_95)/slope)+time_95;
start_time=time_95-((vel_95-0)/slope);
t2p=peak_time-start_time;

```

List of Symbols, Abbreviations, and Acronyms

AA	anti-alias
dB	decibel
g	acceleration due to earth's gravity
Hz	hertz
kHz	kilohertz
LFT&E	Live Fire Test and Evaluation
m/s^2	meter per second squared

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